

# Scour pattern in front of vertical breakwater with wave overtopping

M. Tahersima<sup>†</sup>, A. Yeganeh-Bakhtiary<sup>‡</sup> and F. Hajivalie<sup>∞</sup>

<sup>†</sup> School of civil Engineering, Iran University of science and Technology, 16765, Tehran, Iran  
<sup>‡</sup> Enviro-Hydroinformatic COE, School of Civil Engineering, Iran University of science and Technology, 16765, Tehran, Iran  
<sup>∞</sup> f\_hajivalie@iust.ac.ir  
m\_tahersima@civileng.iust.ac.ir yeganeh@iust.ac.ir



## ABSTRACT

Tahersima, M., Yeganeh-Bakhtiary, A. And Hajivalie, F., 2011. Scour pattern in front of vertical breakwater with wave overtopping. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 7; : – 824. Szczecin, Poland, ISSN 0749-0208

A process-based model is employed to study the scour pattern due to wave overtopping in front of vertical breakwater. The flow field was computed using the RANS equations with a  $k-\varepsilon$  turbulence closing model; while the free surface was tracked using the Volume-Of-Fluid technique. This hydrodynamical model was supplemented with a sediment transport formula to calculate the bed profile changes during scour process. The numerical model is validated against the experimental data for standing waves with and without wave overtopping and a very reasonable agreement was observed between them. The process based model was found to predict well cross-shore sediment transport and thus it provides a tool for predicting beach morphology change. The scour/deposition pattern was quite different for the wave overtopping compare to fully standing waves formation in front of the vertical breakwater. The recirculating cells of steady streaming are the most effective parameter in the formation of scour/deposition pattern in front of vertical breakwaters.

**ADDITIONAL INDEX WORDS:** *Sediment transport, vertical breakwater, bed profile, wave overtopping*

## INTRODUCTION

Vertical breakwaters are mainly constructed for protection of coastal area exposed to high waves in rather deeper part of nearshore zone. The incident high waves impinge on and the reflected wave generates standing waves in front of the vertical breakwater. These waves develop a field of recirculating cells of steady streaming system as shown in Fig. 1. The hydrodynamics of standing wave is rather complex and consisted of the recirculating cells of steady streaming, which plays a crucial role in the stability of vertical breakwater. There is a strong correlation between the local scouring and the steady streaming occurs in front of vertical breakwater. Local scouring in front of a vertical breakwater not only can threaten the structural stability but also may lessen its performance (Lee and Mizutani, 2008).

The wave overtopping has significant effects on the hydrodynamics of flow field in front of vertical breakwater. In other words, the characteristics of standing waves changes from the fully to partial standing waves. Since the recirculating cells are the most effective parameter in the formation of scour/deposition pattern in front of vertical breakwaters.

The significance of steady streaming in scouring near a vertical breakwater has provided the impetus for a number of investigations. The generation of steady streaming and its effect on scour pattern in sand beds under the standing waves near a vertical breakwater has been studied thoroughly by different researchers (e.g. Carter *et al.*, 1973; Mei, 1989; Xie, 1981). Xie (1981) studied the scour pattern.

Zhang *et al.* (2001) carried out experiments on the kinematic and dynamic characteristics of the partially standing waves including measurement of the maximum horizontal velocity of water particles near the node of standing waves in front of a vertical breakwater. They studied the effect of wave overtopping

on the kinematic characteristics and pointed out that the maximum horizontal velocity of water particles decreases slightly.

On the other hand, the limitation in experimental equipment in studying the scour in front of the vertical breakwater is offset with the improvements and developments in numerical modeling capability. Gislason *et al.* (2000) studied the hydrodynamics of the two-dimensional flow in front of a vertical reflective breakwater. This study showed the formation of the generation of circulation cells under the standing waves under the laminar flow conditions. Yeganeh-Bakhtiary *et al.* (2010) developed a numerical model based on the RANS equations with a  $k-\varepsilon$  turbulence closure model to simulate the wave overtopping and its induced hydrodynamics in front of a vertical breakwater. The experimental data of Xie (1981) was used for the model validation. They pointed out that the wave overtopping, prevents the formation of complete recirculating cells of steady streaming, and consequently the formation of scour pattern in front of vertical breakwaters.

Process-based numerical models simulate directly the major processes involved in the scour process using a hydrodynamic model coupled with the sediment transport and bed profile change models. Gislason *et al.* (2009) combined a 2D Navier-Stokes solver with a morphologic model to study scour and deposition in front of breakwaters. The results for scour in front of vertical breakwater were rather consistent with the experimental data, the scour profile in front of the sloping breakwater, however, did not follow the measured profiles.

In this paper, a process-based model is employed to study the scour pattern induced by wave overtopping in front of vertical breakwater. A two-dimensional RANS solver a  $k-\varepsilon$  turbulence closing model is linked with a sediment transport formula to evaluate foreshore morphology. The free surface is tracked with the VOF technique developed by Hirt and Nichols (1981).

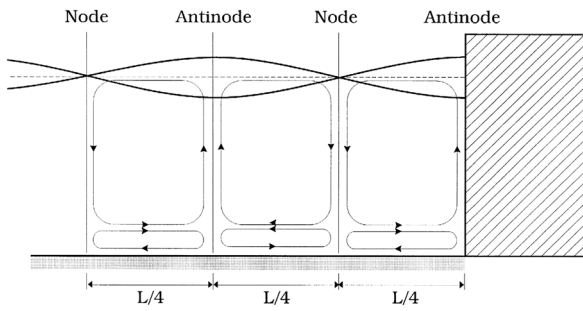


Figure 1. Standing waves and steady streaming in front of vertical breakwater, Sumer and Fredsøe (2000)

The sediment transport formula of Engelund and Fredsøe (1976) and Bijker (1971) are respectively used for expressing the bed load and suspended load. To validate of this assumption, results of numerical methods were compared with experimental works of Xie (1981).

## PROCESS-BASED MODEL

Process-based numerical models directly simulate the major processes involved in scour using a hydrodynamic model coupled with a simple equation for bed profile change. The governing equations for simulation of the wave motion were the Reynolds Averaged Navier-Stokes (RANS) equations in two dimensional coordinates with closing a  $k-\epsilon$  turbulence model with imposing the proper initial and boundary condition (for details see Yeganeh-Bakhtiary *et al.*, 2010). The rate of sediment transport was investigated in several studies (e.g., Frijlink- Kalinske, 1952; Meyer-Peter, 1948; Liu, 2001).

## SEDIMENT TRANSPORT MODEL

### Bed Load Formulation

The transport formula of Engelund and Fredsøe (1976) and Bijker (1971) is adopted respectively to estimate the rate of the bed and suspended and total (bed+suspended) load. Traditionally the transport rate is estimated in terms of bed load and suspended load. The bed load is defined as the part of the total load that is in more or less continuous contact with the bed during the transport (Fredsøe and Deigaard, 1992). Engelund and Fredsøe (1976) presented a formula for estimating the bed load transport which modified with a correction term for gravity and the bed slope as:

$$\frac{q_b}{\sqrt{(s-1)gd^3}} = \frac{a}{\cos \alpha (\mu_c - \tan \alpha)} (\theta - \theta_c) (\sqrt{\theta} - 0.7\sqrt{\theta_c}) \quad (1)$$

where  $q_b$  is the rate of bed load transport in volume of material (per unit width);  $s$  is the specific gravity of sediment grains;  $g$  is the acceleration due to gravity;  $d$  is the sediment size;  $a$  is an empirical constant (taken as 10);  $\alpha$  is the bed-slope angle;  $\mu_c$  is the dynamic Coulomb friction factor (assumed as 0.5); and  $\theta$  is the Shields parameter, which is defined as:

$$\theta = \frac{U_f^2}{(s-1)gd} \quad (2)$$

here  $U_f$  is friction velocity:

$$u_* = U_f = \sqrt{\frac{\tau_b}{\rho}} \quad (3)$$

here  $u_*$  is bottom shear stress and can be computed as:

$$u_* = \sqrt{\left(\frac{1}{2}\right) f \times U} \quad (4)$$

in which  $f$  is wave friction coefficient;  $U$  is velocity of particle. In reality flow is always hydraulically over rough bed.  $f$  which is approximated by Swart formula (1974):

$$f_w = \exp \left( 5.213 \left( \frac{k_s}{A} \right)^{0.914} - 5.977 \right) \quad (5)$$

here  $k_s$  is the bed roughness and can be estimated as:

$$k_s = 2.5d_{50} \quad (6)$$

here  $d_{50}$  is the averaged size sediment particle. With using the linear wave theory the amplitude of the water particle on the bottom can be computed as:

$$A = \frac{H}{2} \cdot \frac{1}{\sinh \left( \frac{2\pi h}{L} \right)} \quad (7)$$

### Suspended Load Formulation

The suspended load is the part of the total load that is moving without continuous contact with the bed as a result of the agitation of fluid turbulence (Fredsøe and Deigaard, 1992). Sediment concentration  $c$  has the unit  $m^3/m^3$ , i.e. the volume of sediments in 1 cubic meter water. The vertical distribution of both the suspended sediment concentration and fluid velocity is presented in Fig. 2 (Liu, Z, 2001):

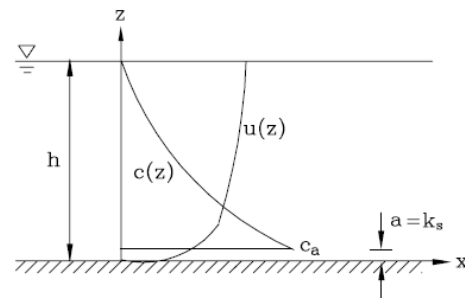


Figure 2. Illustration of vertical distribution of  $c$  and  $u$  (Liu, 2001)

The suspended sediment transport can be obtained as:

$$q_s = \int u(z)c(z)dz = 11.6u_*c_a a \left( I_1 \ln \left( \frac{h}{0.033\kappa_s} \right) + I_2 \right) \quad (8)$$

where  $I_1$  and  $I_2$  are Einstein integrals given by:

$$I_1 = 0.216 \frac{A^{(z_*-1)}}{(1-A)^{z_*}} \int_A^1 \left( \frac{1-B}{B} \right)^{z_*} dB \quad (9)$$

$$I_2 = 0.216 \frac{A^{(z_*-1)}}{(1-A)^{z_*}} \int_A^1 \left( \frac{1-B}{B} \right)^{z_*} \ln B dB \quad (10)$$

here

$$A = \frac{\kappa_s}{h}, B = \frac{z}{h}, z_* = \frac{w_s}{\kappa u_*} \quad (11,12,13)$$

$w_s$  is fall velocity and be defined as:

$$w_s = \frac{\sqrt{\left( \frac{36v}{d_{50}} \right)^2 + 7.5(s-1)gd_{50}} - \frac{36v}{d_{50}}}{2.8} \quad (14)$$

where  $k$  is the Van Karmen constant equal to 0.4.

$$\tau_b = \frac{1}{2} \rho \left( \frac{0.06}{\left( \log \left( \frac{12h}{H_r} \right) \right)^2} \right) U^2 \quad (15)$$

By applying Bijker's (1992) recommendation on  $a$  and  $c_a$ , we have:

$$q_s = 1.83 q_B \left( I_1 \ln \left( \frac{h}{0.033 \kappa_s} \right) + I_2 \right) \quad (16)$$

### Total Load Formulation

Bijker (1971) formula about total sediment transport is:

$$q_t = q_B + q_s = q_B \left( 1 + 1.83 \left( I_1 \ln \left( \frac{h}{0.033 \kappa_s} \right) + I_2 \right) \right) \quad (17)$$

The equation of continuity for sediment (Fredsoe and Deigaard, 1992) is:

$$\frac{\partial q_b}{\partial x} = -(1-n) \frac{\partial h}{\partial t} \quad (18)$$

$h=h(x,t)$  is the time-dependent elevation of the bed surface above a horizontal reference plane;  $x$  is the horizontal coordinate;  $n$  is the porosity of the bed sediment (taken as  $n=0.4$  in the present calculations). With finite difference method we have:

$$\frac{q_i - q_{i-1}}{\Delta x} = -(1-n) \left[ \frac{h_i^n - h_i^{n-1}}{\Delta t} \right] \quad (19)$$

In result:

$$h_i^n = \frac{q_i - q_{i-1}}{\Delta x} \times \frac{-\Delta t}{(1-n)} + h_i^{n-1} \quad (20)$$

Table 1: Model data based on experimental condition of Xie (1981)

D50 ( $\mu\text{m}$ )	T (s)	H (m)	d (m)	L (m)
150	1.17	0.05	0.3	1.714

After implement of these formulas in time increment of 0.1 sec and with horizontal particles velocities near the bed, every new time step height of bed profile obtained from the previous one in numerical calculations. In this study for comparison of results with experimental data, one of the test characteristics of Xie (1981) are implied that observed in Table 1.

## RESULTS AND DISCUSSIONS

### Model Validation

The performance of the model was checked using the experimental data of Xie (1981) and Zhang *et al.* (2001). Firstly, the models result on hydrodynamic of wave overtopping is compared with the experiment of Zhang *et al.* (2001) and then the scour pattern for standing wave in front of vertical breakwater is validated against the experiment of Xie (1981). The experiment of Zhang *et al.* (2001), as shown in Fig.3, was conducted in a 63x 1.25 x 1.25 m wave flume, the elevation of top of the model

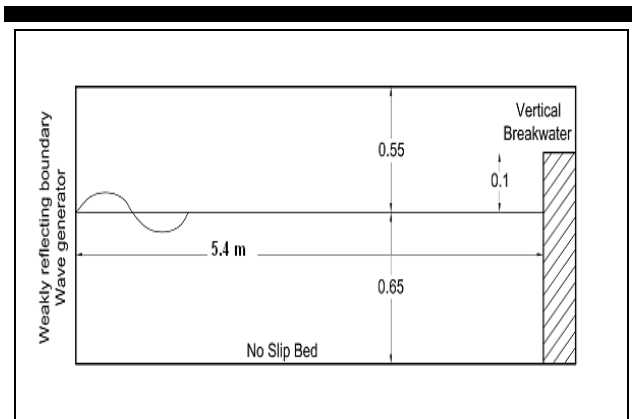


Figure 3. A sketch of numerical domain based on Zhang *et al.* (2001)

breakwater in all of the experimental configurations was 0.75 m, and the incident waves were generated in the still water depth of  $d=0.65$  m. The velocity was measured at a point fixed in 0.675 m from the vertical breakwater and 0.25 from the bottom. Fig. 4 shows the comparison between maximum horizontal velocity of the experiments and that of the numerical model. As can be seen, there is a very good agreement between the model results and the experimental data on flow hydrodynamics. It is noted  $U_m$  and  $U_n$  were denoted respectively as the maximum horizontal orbital velocity measured in the experiment and were computed by the model.

The experiment of Xie (1981) was conducted in a 38 m long, 0.8 m wide and 0.6 m deep wave flume. The water depth was equal to 0.45 m at the beginning of the flume and reached to 0.3 at the flat bed near the breakwater by a 1:30 slope.

The incident waves varied from 5.0 to 9.0 cm and the wave period varied from 1.17 to 3.56 s. The hydrodynamic model has been validated with the experimental data of Xie (1981) and the comprehensive result of flow field was reported in Yeganeh-Bakhtiary *et al.* (2010). Generally, there is a very good agreement between the model results and different experimental data sets on the standing wave hydrodynamics in front of vertical breakwater.

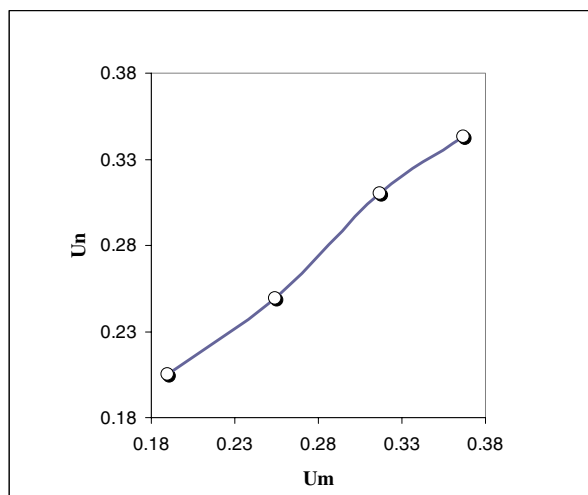


Figure 4. Comparison between numerical results and experimental data of Zhang *et al.* (2001)

### Scour Pattern

Fig. 5 shows the comparison of scour profile of the numerical result with that of the Xie (1981) experimental data for the no suspension case. As can be seen, the scour pattern estimated by the model agrees very well with the experiment, a slight deviation, however, from the experimental data could be observed at the distance of about  $L/2$  away from the breakwater. The maximum scour depth in the selected test case was  $1.50\text{ cm}$ ; while, the calculated maximum scour depth was  $1.65\text{ cm}$ , which agrees well with the experiment. Thus the model was successful in the calculation of scour pattern as well as the maximum scour depth. As already mentioned, the scour pattern is responding to dynamics of the steady streaming formation in front of the vertical breakwater.

The time development of bed profile for no-suspension scour mode under standing wave condition in front of the vertical breakwater is depicted in Fig. 6. As can be seen in the figure, bed profile emerges in the form of alternating scour and deposition areas in front of vertical breakwater and the rate of scour/deposition increase with time till it reaches to the equilibrium condition. The maximum scour depth as expected is approximately took place at  $L/4$  after the first deposition near the vertical breakwater and the maximum scour reached almost to  $1.6\text{ cm}$  for the equilibrium condition.

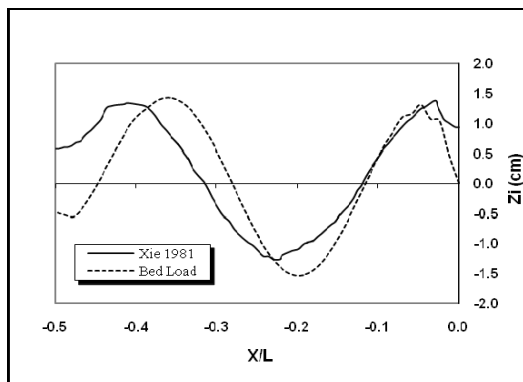


Figure 5. Comparison of scour pattern between numerical model and experimental data (Xie, 1981) for bed load

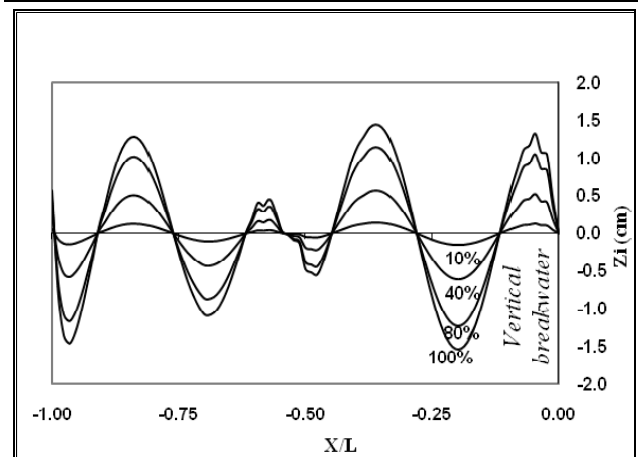


Figure 6. Time development of bed profile for no-suspension scour mode, standing wave condition

The time development as well as the spatial distributions of bed profile for no-suspension scour mode with wave overtopping in front of vertical break water is shown in Fig.7. As expected the rate of scour/deposition increase with time till it reaches to the equilibrium condition. However, a different trend in the scour/deposition pattern can be observed in the case of the wave overtopping. Firstly the maximum scour depth at the equilibrium condition in the case of the wave overtopping is reached to  $4.0\text{ cm}$ , which is approximately three times as large as that of the standing waves in front of vertical breakwater. While similar to the standing wave case the maximum scour depth took place at  $L/4$  after the first deposition near the vertical breakwater. In addition, the second scour deposition bar from the breakwater is almost diminished.

To investigate the suspended sediment effects on the scour deposition pattern under wave overtopping, the time development of bed profile for total transport (considering bed load and suspended load simultaneously) is simulated with the process based model and the result is presented in Fig. 8. It can be seen from the figure, the suspended sediment has a significant effect on the formation of alternating scour and deposition in front of vertical breakwater. The deposition bar at the close vicinity of vertical was totally vanished. The rate of scour/deposition increase with time till

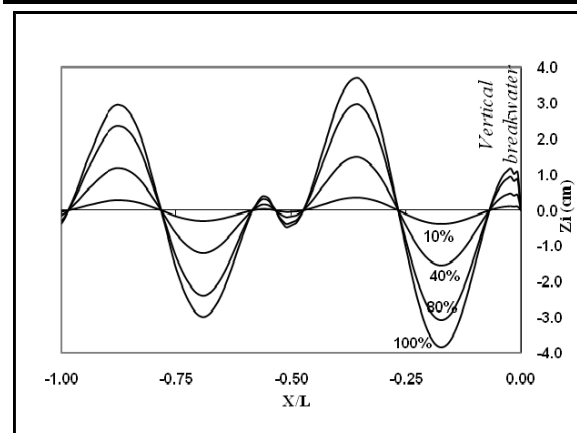


Figure 7. Time development of bed profile for no-suspension scour mode, standing wave condition

it reaches to the equilibrium condition. In addition the maximum scour depth at the equilibrium condition and its location is virtually in identical to the no-suspension scour mode.

The different trend of the scour/deposition pattern in the case wave overtopping in front of vertical breakwater can be attributed to the influence of wave overtopping on the steady streaming patterns of both the fully and partially standing waves were explored sophisticatedly near vertical breakwater. In other words, the wave overtopping modifies both the dynamics of the standing waves and the flow conditions at the vicinity of the vertical breakwater.

As Yeganeh-Bakhtiary (2010) discussed earlier the recirculating cells of steady streaming clearly are generated in front of the vertical wall for standing waves in front of vertical breakwater, whereas due to the influence of overtopping the recirculating cells were significantly changed and the vectors of averaged velocity tend to have a coastward direction. In other words "when wave overtopping occurs, part of the wave energy is dissipated by the uprushing water body, causing the reflected wave energy and velocity to be reduced. It conduces to disturb the regular system of standing waves and the steady streaming is not completely generated at this condition because of the similar effects on the vertical and horizontal orbital velocities at nodes and anti-nodes". This corresponds to the wave celerity and wave length being smaller that changes the wave condition from fully the partially standing waves due to the overtopping. "Therefore, the partially standing waves become more asymmetric and will gradually be deformed in front of the vertical wall. This created a shift in the phase between the fully and partially standing waves due to overtopping". Since the recirculating cells of steady streaming are the most effective parameter in the formation of scour/deposition pattern in front of vertical breakwaters, the scour/deposition pattern was quite different for the wave overtopping in front of the vertical breakwater.

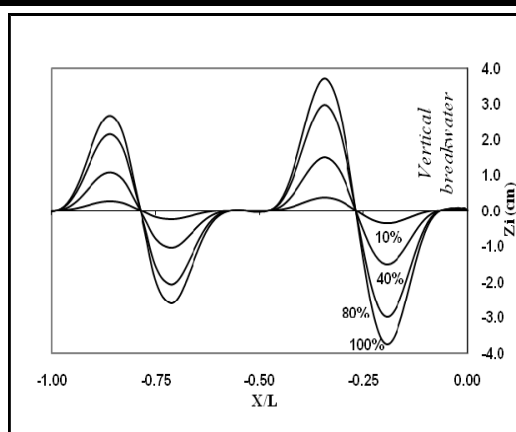


Figure 8. Time development of bed profile for total scour mode, standing wave condition

## CONCLUSION

A process-based model is employed to study the scour pattern due to wave overtopping in front of vertical breakwater. The model is based on the Reynolds Averaged Navier-Stokes (RANS) equations, with a free surface detector (VOF) and the  $k-\varepsilon$  turbulence closure model. This model was supplemented with a sediment transport formula to calculate the bed profile changes during scour process. The numerical model is validated against the experimental data for standing waves with

overtopping and a very reasonable agreement was observed between them. The model was then coupled with a sediment transport formula and a simple model for the bed profile changes, performed to investigate to study the scour pattern due to wave overtopping. From the analysis of the numerical result, the following conclusions are drawn:

- The process-based model accurately estimated the scour/deposition pattern for no suspension mode of scour in front of vertical breakwater. The model approach may prove useful for simulating the scour under wave overtopping in front of vertical breakwater.
- The scour/deposition pattern was quite different for the wave overtopping compare to standing waves formation in front of the vertical breakwater.
- The recirculating cells of steady streaming is the most effective parameter in the formation of scour/deposition pattern in front of vertical breakwaters.

## LITERATURE CITED

- Bijker, E.W., 1971. Longshore transport computation. *Journal of Waterways, Harbors and Coastal Engineering Division*, ASCE: 97(WW 4); 687-701.
- Carter, T.G., Liu, L.F.P. and Mei, C.C., 1973. Mass transport by waves and offshore sand bed forms. *Journal of Waterway Harbors and Coastal Engineering*, ASCE, Vol.99. No. WW2, pp. 165-184.
- Engelund, F.A and Fredsøe, J., 1976. A sediment transport model for straight alluvial channels. *Nordic Hydrology*: 7 (5); 293-306.
- Fredsøe, J and Deigaard, R., 1992. Mechanics of Coastal Sediment Transport. *World Scientific*, Singapore. 369 pp.
- Frijlink, H.C., 1952. Discussion des formules de debit solide de Kalinske, Einstein de Meyer-Peter et Mueller copte tenue des mesures recentes de transport dans les rivières Neerlandaises, *2me Journal Hydraulique Societe Hydraulique de France*, Grenoble, 98-103.
- Gislason, K., Fredsøe, J., Mayer, S. and Sumer, B.M., 2000. The mathematical modeling of the scour in front of the toe of a rubble-mound breakwater. 2000. In: *Book of abstracts, 27th international coastal engineering conference*. Vol. 1. Sydney (Australia): ASCE, Paper No. 130.
- Gislason, K., Fredsøe, J and Sumer, B.M., 2009. Flow under waves Part 2. Scour and deposition in front of breakwaters, *Coastal engineering* 56; 363-370
- Hirt, C.W. and Nichols, B.D., 1981. Volume of fluid (VOF). method for the dynamics of free boundaries. *Journal of Computational Physic*, ;39, 201-25.
- Lee, K., Mizutani, N., 2008. Experimental study on scour occurring at a vertical impermeable submerged breakwater. *Journal of Applied Ocean Research*, 30(2):92-99.
- Liu, Z. 2001, Sediment Transport, p 66.
- Mei, C. (1989), The Applied Dynamics of Ocean Surface Waves, *World Sci.*, Hackensack, N. J.
- Meyer-Peter, E. and Müller, R., 1948. Formulas for bedload transport, *2nd IAHR Congress*, Stockholm, 39-64.
- Swart, D.H. 1974. Offshore Sediment Transport and Equilibrium Beach Profiles. *Doctorate Dissertation*, Dept. of Civ. Engineering, Delft Univ. of Technology, The Netherlands.
- Zhang, S., Cornett, A., Li, Y., 2001. Experimental study of kinematic and dynamical characteristics of standing waves. In: *Proceeding 29th IAHR conference*.
- Yeganeh-Bakhtiary, A., Hajivalie, F and Hashemi-Javan, A., 2010. Steady streaming and flow turbulence in front of vertical breakwater with wave overtopping, *Applied ocean Research* 32; 91-102.